LOIs and Perspectives from Atmospheric/LBL Measurements

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NF02 Mini-Workshop

Atmospheric/Long-Baseline LOIs

- 14 LOIs covering sterile searches in atmospheric and/or long-baseline experiments
  - Covering general approaches, current experiments, and future or proposed experiments

- General approaches
  - Long-Baseline Accelerator Probes for Light Sterile Neutrinos
  - Sterile Neutrino Searches with Atmospheric Neutrinos
  - Physics with Sub-GeV Atmospheric Neutrinos
  - Tau Neutrino Physics

- Current Experiments
  - T2K
    - T2K Experiment: Future Plans and Capabilities
  - NOvA
    - The NOvA Physics Program through 2025
    - The NOvA Experiment and Exotic Neutrino Oscillations
  - IceCube
    - Neutrino Oscillations with IceCube-DeepCore and the IceCube Upgrade
    - BSM Neutrino Oscillation Searches with 1-100 TeV Atmospheric Neutrions at IceCube

- Future/Proposed Experiments
  - Hyper-Kamiokande
    - The Hyper-Kamiokande Experiment
  - DUNE
    - Physics Beyond the Standard Model in DUNE
    - DUNE Near Detector
    - Atmospheric ν_τ Appearance in the Deep Underground Neutrino Experiment
  - THEIA
    - Long-Baseline Neutrinos at THEIA

General Approaches

Long-Baseline Accelerator Probes for Light Sterile Neutrinos

- Short-baseline experiments (LSND, MiniBooNE) have reported significant excesses in the electron (anti)neutrino channels
  - Possibly due to the existence of an eV-scale sterile neutrino
- SBL experiments typically probe L/E ~ 1 km/GeV
- LBL experiments typically probe L/E ~ 1000 km/GeV (at the far detector)
- Why are LBL sterile neutrino searches useful?

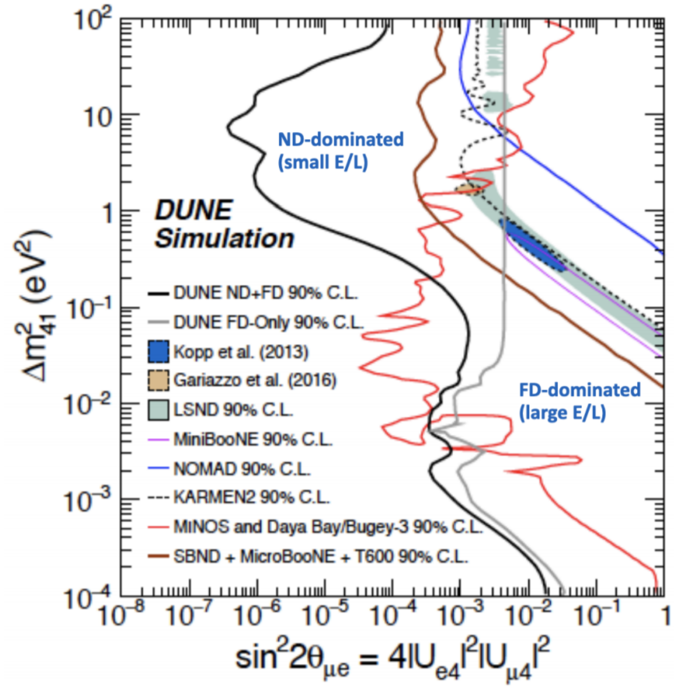
Long-Baseline Accelerator Probes for Light Sterile Neutrinos

- Disappearance between near and far detectors
  - SBL electron neutrino appearance is driven by $\sin^2 2\theta_{\mu e}$
  - LBL disappearance is driven by $\sin^2 2\theta_{\mu\mu}$ (muon neutrino) and $\sin^2 2\theta_{ee}$ (electron neutrino)
  - Appearance is quadratically suppressed compared to disappearance measurements
- In current generation, necessary to combined reactor and LBL results, but in future high-intensity experiments, can be done with a single experiment's data

$$sin^2 2\theta_{\mu e} = 4|U_{e4}|^2|U_{\mu 4}|^2$$

$$sin^2 2\theta_{\mu\mu} = 4|U_{\mu 4}|^2(1-|U_{\mu 4}|^2)$$

$$sin^2 2\theta_{ee} = 4|U_{e4}|^2(1-|U_{e4}|^2)$$



Long-Baseline Accelerator Probes for Light Sterile Neutrinos

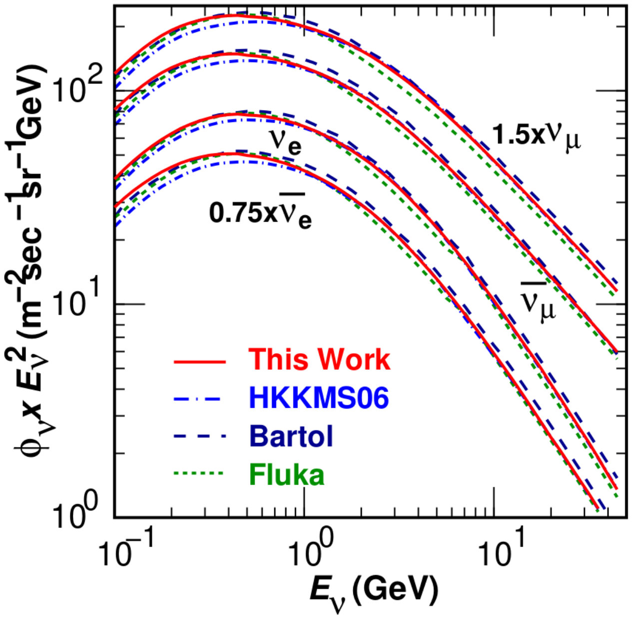
- NC disappearance
  - NC rate is insensitive to 3 flavor oscillations
    - three active flavors have same NC cross section
  - Sterile appearance looks like depletion of NC rate
  - Terms depending on atmospheric frequency make far detector sample sensitive to sterile neutrinos regardless of the sterile mass scale

$$
\begin{aligned}
1 - P(\nu_\mu \to \nu_s) \approx\ & 1 - \cos^4\theta_{14}\cos^2\theta_{34}\sin^2 2\theta_{24}\sin^2\Delta_{41} \\
& - \sin^2\theta_{34}\sin^2 2\theta_{23}\sin^2\Delta_{31} \\
& + \frac{1}{2}\sin\delta_{24}\sin\theta_{24}\sin 2\theta_{23}\sin\Delta_{31},
\end{aligned}
$$

- Combined SBL and LBL strengths
  - Highly capable near detectors, necessary to understand beam and cross section effects in 3 flavor analyses, are capable of observing SBL oscillations
  - Since oscillations are L/E dependent, but beam and cross section effects are not, a joint analysis across both detectors can help disambiguate effects
    - Especially helpful if detectors contain the same target nuclei

Sterile Neutrino Searches with Atmospheric Neutrinos

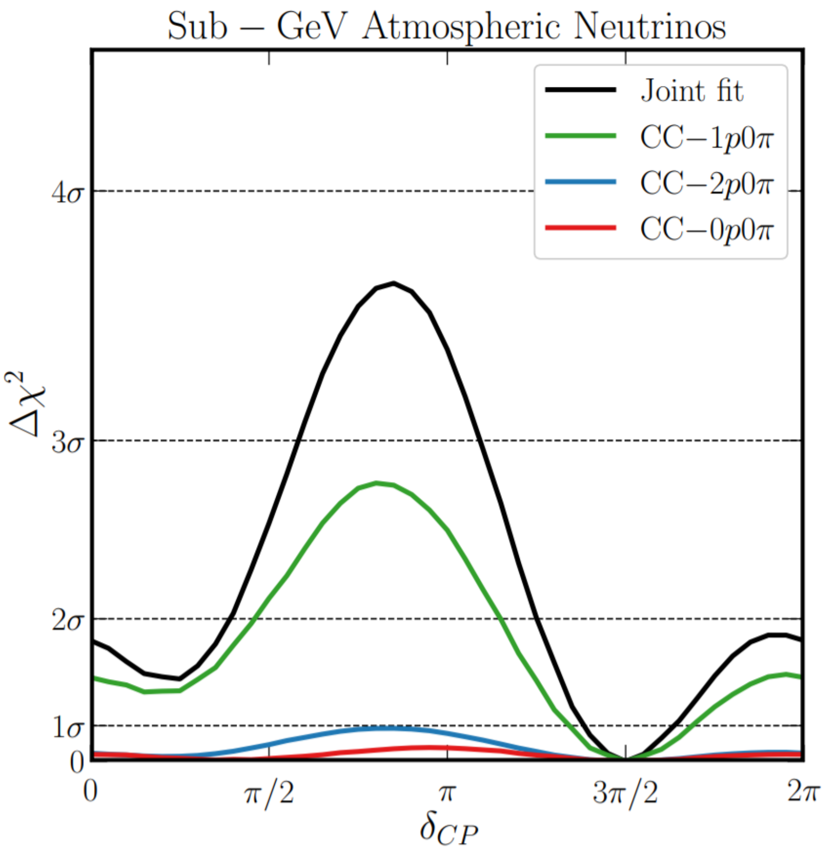
- Atmospheric fluxes span range from MeV to multi-TeV scales
  - High energies provide opportunities to also measure tau neutrino appearance, permitting searches for $|U_{e4}|^2$, $|U_{\mu4}|^2$, $|U_{\tau4}|^2$, and $|U_{s4}|^2$ matrix elements simultaneously
- Neutrino path lengths vary between ~15,000 km and ~28,000 km
- Neutrinos are exposed to a wide range of matter effects depending on path through Earth
  - At high energies, MSW resonance dramatically enhances muon neutrino disappearance, if eV-scale steriles exist
- Broad L/E and matter-effect ranges complement LBL searches
  - Experiments like Hyper-Kamiokande and DUNE will be able to combine strengths of LBL and atmospheric searches to further constrain systematic uncertainties
    - If higher energy beam running is possible, better cross section and detector effect constraints for atmospheric analyses may be possible



M. Honda, T. Kajita, K. Kasahara, and S. Midorikawa, Phys. Rev. D 83, 123001 (2011)

Physics with Sub-GeV Atmospheric Neutrinos

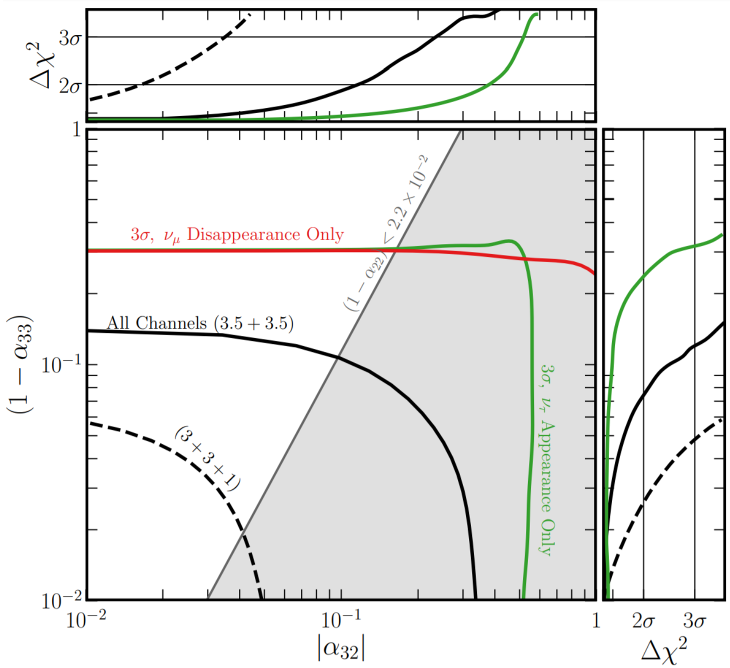
- Atmospheric neutrinos with energies between 100 MeV and 1 GeV have a rich phenomenology
  - Oscillations are affected by strongly by both solar and atmospheric splittings
    - Enhances interference between amplitudes and CP violation effects
  - Oscillations affected by MSW and parametric resonances, further increasing the CP-interference term
- Liquid argon TPCs should be capable of reconstructing these low energy events with sufficient energy and angular resolution to perform an oscillation analysis
- Since sample has a distinct phenomenology from accelerator or higher energy atmospheric samples, it provides another handle for disambiguating oscillations and systematics in a combined analysis



Sensitivity to CP-violation at DUNE using only the sub-GeV atmospheric neutrino sample

Tau Neutrino Physics

- Total number of recorded tau neutrinos in high purity samples consists of 10s of events
  - Tau neutrinos are the least well studies particle in the Standard Model
- A high-purity, high-statistics sample of tau neutrinos provides opportunities to test the 3 flavor model
  - Tau neutrino appearance must be consistent with measurements of muon neutrino disappearance and electron neutrino appearance
- Tau neutrino appearance provides an addition handle to constrain $|U_{\tau 4}|^2$
- If sterile neutrinos exist, but are too heavy to be kinematically accessible, the observed PMNS matrix will be non-unitary
  - 3x3 matrix would be a sub-matrix of the larger, true PMNS matrix
- Tau neutrino appearance, in combination with muon neutrino disappearance and electron neutrino appearance can lead to stringent constraints on non-unitarity



A. de Gouvea, K. Kelly, G. V. Stenico, P. Pasquini, Phys. Rev. D 100, 016004.

Sensitivity to non-unitarity parameters α_{32} and α_{33} using DUNE electron, muon, and tau neutrino samples

Current Experiments

T2K

- Near site: 280 m baseline
  - On-axis INGRID detector for beamline monitoring
  - Off-axis ND280 detector with multiple detector systems to isolate exclusive interaction types to improve predictions at the far site
  - Off-axis WAGASCI+BabyMIND detector for measuring the water to hydrocarbon cross-section ratio
- Far site: 295 km baseline
  - Off-axis 50 kt water-Cherenkov Super-Kamiokande detector
- Upgrades:
  - Increasing the beam power to 1 MW
  - Add fully active target to ND280 and increase angular acceptance using new horizontal TPCs
- Current sterile neutrino searches use an array of muon neutrino and neutral current disappearance samples under the assumption that oscillations occur only at the far detector
- The NCQE sample provides a unique low energy neutral current probe
- T2K expects to continue taking data until the start of Hyper-Kamiokande, reaching $10\text{x}10^{21}$ POT

NOvA

- Two functionally identical, off-axis, liquid scintillator tracking calorimeters
  - Near site: 1 km baseline, 300-ton detector
  - Far site: 809 km baseline, 14 kt detector
- Current sterile analyses takes advantage of narrow-band beam centered at the first atmospheric oscillation maximum
  - High purity NC sample at atmospheric oscillation maximum gives access to oscillation probability terms independent of the sterile mass splitting
  - Functionally identical detectors partially cancel correlated uncertainties
- Future sterile analyses
  - Developing a two-detector fit technique to account for possible oscillation in the near detector
  - Uses a covariance matrix technique to account for correlated uncertainties between detectors
  - Hybrid Poisson likelihood and covariance matrix technique will allow for the inclusion of muon neutrino samples
- Beam upgrades are in progress designed to increase the NuMI beam power from 700 kW to > 900 kW
- NOvA expects to continue taking data through 2025, collecting a total of 63×10^{20} POT (2.4x current exposure if all beam improvements are realized)

IceCube

- IceCube consists of a sparse array of strings of optical modules embedded in the ice of Antarctica with a high energy threshold, but capable of measuring events into the PeV scale
  - Current sample of 300,000 high energy neutrinos
  - Large matter effects lead to significant sensitivity to eV-scale sterile neutrinos
  - Systematics controlled at 1-2% per bin
  - Future plans:
    - Integrate cascade sample which has better energy resolution to help resolve MSW resonance
    - Combine track and cascade samples to constrain angles beyond θ_{24}
- The DeepCore detector is a dense in-fill of the IceCube array instrumenting 10 Mton of ice, sensitive to the energy range of 5 – 100 GeV
  - Current sample of > 300,000 neutrinos
  - Capable of detecting ~18,000 tau neutrino events
    - ~15% precision on tau neutrino normalization expected for 8 year analysis
  - Comparable L/E to LBL experiments, but with higher energy
    - Same measurements with different cross section uncertainties
- IceCube Upgrade
  - Planned extension of higher density sub-array within DeepCore with a 2 Mton fiducial mass
  - Lower energy thresholds and improved efficiencies
  - Improved detector and ice property calibrations to feed into both high and low energy analyses
  - Expected to achieve 10% precision on tau neutrino normalization in a single year

Future/Proposed Experiments

Hyper-Kamiokande

- Hyper-Kamiokande will consist of a water-Cherenkov detector with an 217 kt inner detector region
  - PMTs will have improved QE, timing, and noise compared to Super-K
- Will be located off-axis from the T2K beam, and use the upgraded near detector complex from the T2K experiment
- Intermediate Water Cherenkov Detector, a 1 kt detector will be located 750 m from the target
  - IWCD will be capable of being moved to different off-axis positions to better measure cross sections and constrain intrinsic electron neutrino backgrounds

DUNE

- DUNE is a next-generation, LBL experiment consisting of a 40 kt liquid argon TPC deep underground with a 1300 km baseline
  - The far detector is located on-axis and is exposed to a broad band beam
- The near detector complex at Fermilab consists of a liquid argon TPC, a high pressure gas TPC, and a scintillator tracker similar to the tracker developed for the T2K upgrade
  - The two TPCs will be capable of moving off-axis to observe a series of narrow band beams
    - This will be used for deconvolving flux and cross section models
  - The scintillator tracker remains on axis and acts as a beam monitor
- DUNE will have high enough statistics to not only search for sterile neutrinos through neutral current disappearance, but also electron and muon neutrino disappearance
- DUNE will also collect a large atmospheric sample which spans a broad range of L/E, and will contain a substantial number of tau neutrinos
  - The high resolution LArTPC will permit the selection and reconstruction of a pure sample of tau neutrinos
  - Since DUNE has a broad band beam, the beam tail will also produce substantial tau neutrino appearance

THEIA

- Water-based liquid scintillator detector
- Sensitive to both scintillation and Cherenkov light
  - Scintillation light provides background rejection and makes slow particles visible
  - Cherenkov light provides directional reconstruction and particle ID at high energies
- Plans have been developed for both a 25 kt and 100 kt detector
- THEIA25 is a candidate to serve as the 4th module of the DUNE far detector
  - In this case, the scintillator tracker would serve as a near detector for THEIA
- THEIA could improve the sterile sensitivity of DUNE due to helping disentangle beam and cross section effects, as well as through its low energy threshold

Summary

- Current state of the sterile neutrino field is unclear
  - Some significant signals in short baseline accelerator and reactor experiments
  - Signals strongly disfavored by long-baseline accelerator experiments
- Understanding how these current observations fit together will require an array of complementary approaches
- LBL experiments provide opportunities to
  - measure neutral current disappearance at the atmospheric frequency
  - measure electron and muon neutrino disappearance for a strong constraint on potential sterile driven electron neutrino appearance
  - leverage SBL measurements at the ND to separate potential oscillations from beam, cross section, or detector systematic effects
- Atmospheric experiments provide access to
  - a large L/E range to cover a broad range of parameter space
  - large matter effects to modify sterile transitions
  - a tau neutrino appearance sample to constrain the unitarity of the PMNS matrix
- Next generation experiments will be both highly capable LBL and atmospheric experiments providing
  - high statistics for unambiguous inference
  - redundantly controlled systematics
  - rich samples for distinguishing models